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GEOPHYSICAL INSTITUTE
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Technical Summary Report
SPECTROPHOTOMETRY OF ATMOSPHERIC EMISSIONS
HEADQUARTERS, UNITED STATES AIR FORCE
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This is the quarterly report for the contract period 15 September through 15 December 1965 on Contract AF 33(657)-13703. The work completed during this quarter is summarized below according to task.

Task A. Twilight and Day Airglow

A method of scanning a small wavelength interval of the optical spectrum using a narrow band interference filter and a moving axicon lens has been developed. It is suggested that this system could be used for the detection of lithium emission in the twilight in order to reduce the possibility of auroral contamination and provide wavelength identification of the signal.

Task B. Fast Fluctuations of Aurora and Airglow Emissions

Fast auroral waves, previously identified in the absence of any auroral forms other than the arc from which they apparently emanated, have now been observed to occur during a pulsating aurora display. The waves were substantially the same type as those observed earlier and were differentiated from the pulsating patches by their fast southward motion across the sky and their greater latitudinal extent (up to 200 km).

Some preliminary results of an attempt to find a mechanism for the generation of the fast auroral waves are presented.

Task A. Twilight and Day Airglow

Technical efforts in the second contract year have been concentrated toward the development of a photometer or other device which would result in positive identification of the lithium line in twilight, and in the separation of this signal from the auroral N_2 1st positive emission at $\lambda 6704$. This photometer would be required to detect an emission line of brightness 20 to 200R at 6708A while rejecting several kilorayleighs of auroral emissions peaking at 6704A. The detection must be made against the continuum of scattered light in twilight which has an intensity of about 200R/A (at 6° solar depression angle).

The birefringent filter photometer has been used in this situation quite successfully, but even if such an instrument is designed to eliminate the auroral contamination, there is always the question as to whether the signal was actually due to the lithium doublet. For obvious reasons, positive wavelength identification is desirable.

The first instrument which comes to mind in considering spectral line identification is some sort of photoelectric scanning spectrometer. However, even with high quantum efficiency and memory circuits, the lithium line would be too faint for the spectrometer whose slit area (one of the main factors determining its threshold of sensitivity) would approach at most 1 cm^2 , while the entrance area of the birefringent filter photometer is over 100 cm^2 .

It was this consideration which led to the development of the narrow band (1 to 3A) interference filter as a means of isolating a small wavelength region with good photometric sensitivity. Theoretically, it can have a relatively large area, and the discrimination against a background continuum can be accomplished by taking advantage of the sensitivity of the wavelength interval of the band pass on the angle at which the incoming light is incident on the

filter. A review of the possibilities of tilting the filter to modulate the emission line and not the continuum was given in an earlier report. Briefly, it consisted of tilting the filter at a constant rate so as to modulate the emission line by including it in the bandpass at one position and not in the other; electronic comparison of the two signals should give the brightness of the emission line alone. The problem in designing such a photometer arises in trying to match the etendues of the various components of the photometer. That is, the critical dependence of bandpass position on angle of incidence ($\pm 1/2^\circ$) presents serious restrictions on the aperture of the system. This factor, combined with the difficulties of keeping the chopping frequency constant (especially in a balloon package of less than 10 lbs.) has led us to consider other methods of wavelength separation. The first method to be considered was one similar to that described by Shepherd, et al (Appl. Opt. 4, No. 3, 267, 1965). We considered recording the light passing through the filter at two different angles using fiber optics and two photomultipliers.

This system is superior to the tilting filter method but the main objection to it is inherent in any system which involves looking through the filter at two constant angles: if the filter bandpass changes slightly in wavelength due to filter aging, or ambient temperature fluctuations, a false signal would result. "Tuning" such a fixed geometry is difficult.

Thus, since wavelength identification is a major concern (the birefringent photometer has enough sensitivity to detect lithium emission), a method of scanning in wavelength and still maintain a large aperture was developed. The continuous scanning of the "free spectral range" of the interference filter (or Fabry-Perot Etalon) is accomplished with an axicon lens, as described by Katzenstein (Appl. Opt. 4, No. 3, 263, 1965). A diagram of the system is shown in Fig. 1. Light passing through a narrow band interference filter at a given angle is focused by an ordinary lens and bent into an aperture by the axicon

lens. Motion of the axicon refracts light from different angles (and therefore different wavelengths) into the aperture and onto a photomultiplier. In effect, the passband of the filter is scanned through a small wavelength interval about the emission line of interest as the axicon is moved along the optic axis.

This system has been used successfully on the aurora. Figure 2 shows a trace of several scans of a 2 in. dia. 2.6A interference filter peaked in transmission at 5584A. The peak transmission (40%) of the $\lambda 5577$ line occurs at 5 degrees off the normal to the filter. A 30° axicon was used with a 3mm aperture. The axicon was scanned through 6 inches starting 2 inches in front of the aperture. An RCA 7265 photomultiplier was placed 1 inch from the aperture.

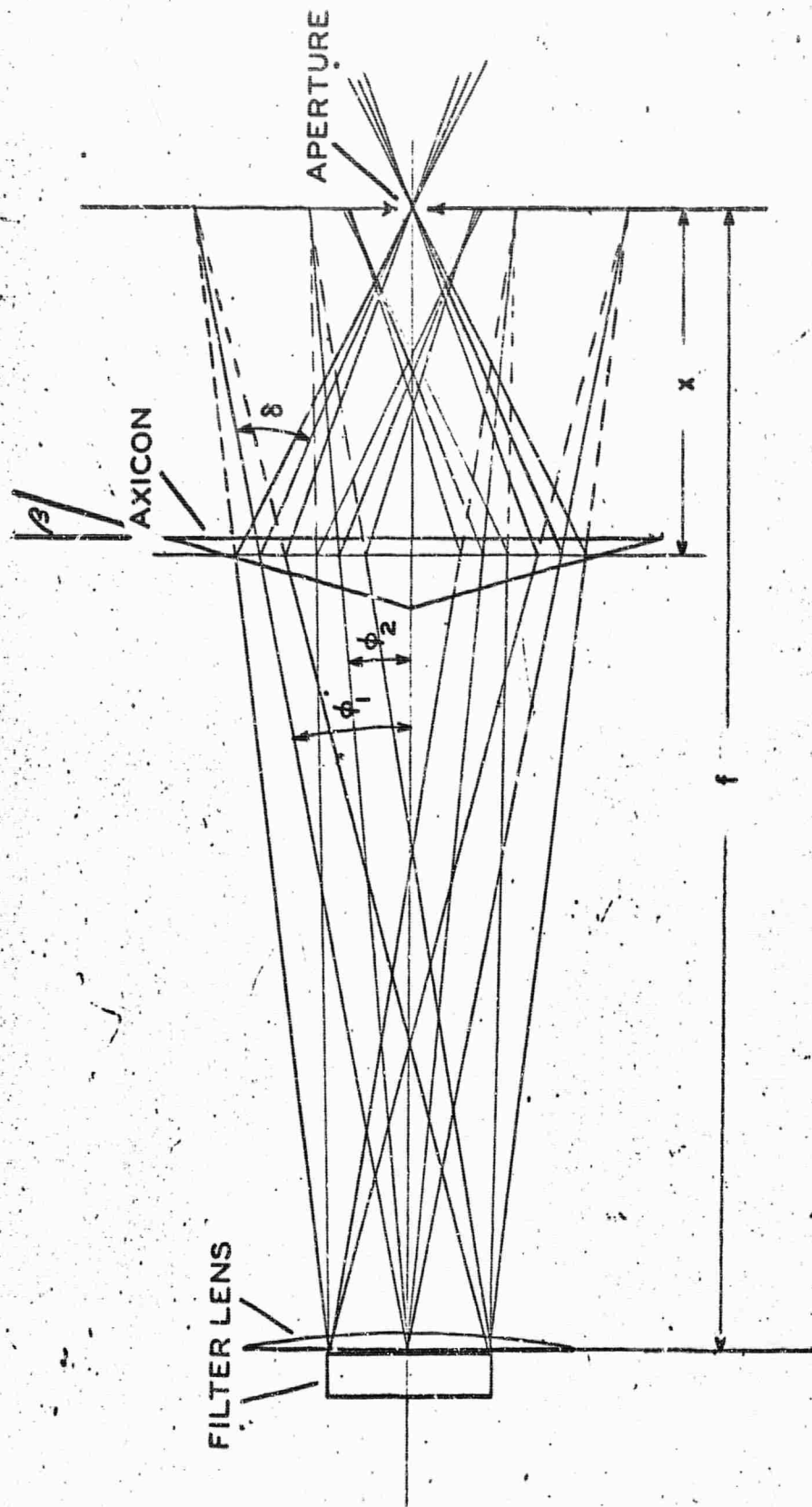
The 5577A emission was about 1 kR during the time the scans were made. The difference in peak height from scan to scan is due to the changing brightness of the aurora. The duration of each scan was 30 seconds.

If the system proves to be sensitive enough to detect the low light level of the lithium twilight emission, the question remaining is how to discriminate against the scattered sunlight. Perhaps the most expedient method is to take advantage of the fact that the scattered sunlight at 90° to the sun is over 60% polarized while the lithium emission is not more than 10% polarized. The simple procedure of orienting a polaroid so as to minimize the scattered light signal may be sufficient since the 200 R/A of scattered sunlight in the 6708A region would be reduced to about 50 R/A which is 150 R for a 3A filter. Signals one tenth of the total should be easily recorded.

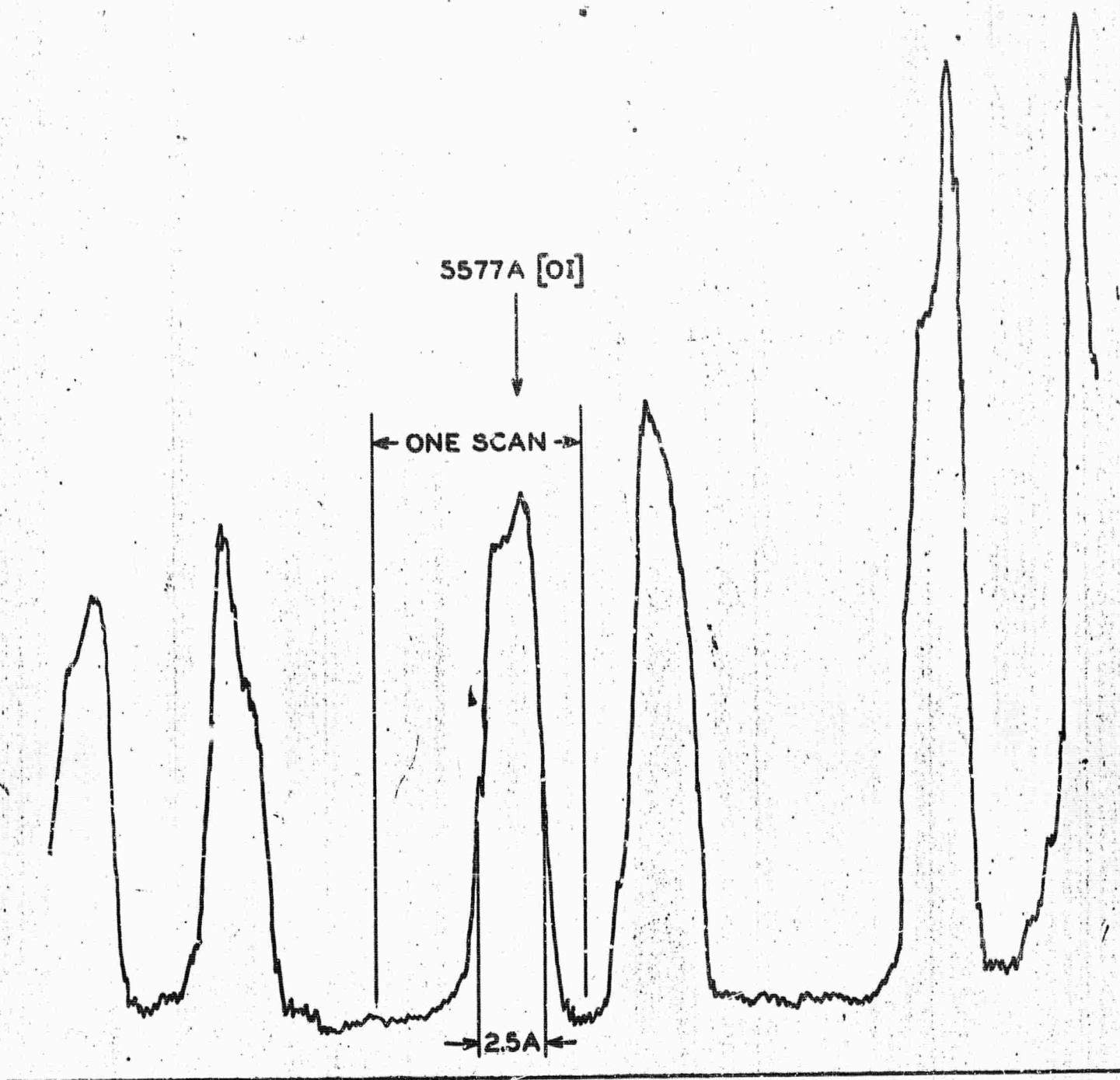
If the simpler methods are not adequate, the instrument could be converted

to a differential polarimeter. This device would use a method developed by Noxon for the detection of $\lambda 6300$ [OI] dayglow. This type of instrument usually consists of a device with a narrow optical passband which is scanned through a small wavelength interval including the emission of interest. The sky light is separated into two beams, one including the polarized component and the other excluding it. The difference of these signals is set to zero at the beginning of the wavelength scan. It is this property, first used by Noxon, which enables the instrument to separate the unpolarized dayglow from the strongly polarized sunlight.

Thus, it is our present intent to continue attempting to detect natural lithium emission with emphasis on wavelength discrimination. It is felt that this will increase confidence in the observations and prevent auroral interference.



TASK A Figure 1. A ray diagram of an axicon-scanned interference filter. The aperture is placed at the focal plane of the lens. The concentric rings of light which pass through the filter at various angles are bent to the optic axis by the axicon. In this case, light passing through the filter at ϕ_1 passes through the aperture and light at ϕ_2 does not. Motion of the axicon along the optic axis(x) presents different angles (ϕ) to the aperture according to the equation $f\phi = x\delta(\delta = [1-n]\beta$, where n is the index of refraction of the axicon material and β is the axicon angle).



TASK A Figure 2. Axicon scans of a 2 inch dia., 2.5A half-width, interference filter. The source of $\lambda 5577[OI]$ was a class I aurora.

TASK B. Fast Fluctuations of Atmospheric Emissions

Part I Observations of Fast Auroral Waves in Pulsating Aurora Displays

The existence of waves of light passing through some pulsating aurora displays has been known for many years. A description of a pulsating display observed near FranzJosef's Land was given by Weyprecht who wintered with the Austrian-Hungarian Arctic Expedition in 1872-3. Chapman and Bartels (1940) have quoted his impressions of the nightly auroral cycle there; the section on pulsating auroras is as follows:

"Fragments of the northern lights are strewn on every side; it seems as if the storm had torn the aurora bands to tatters, and was driving them hither and thither across the sky. These threads change form and place with incredible rapidity. Here is one! lo, it is gone! Scarcely has it vanished before it appears again in another place. Through these fragments drive the waves of light: one moment they are scarcely visible, in the next they shine with intense brilliancy. But their light is no longer that glorious pale green; it is a dull yellow."

A similar wave phenomenon was photometrically examined by Cresswell and Belon (1966). However, the "fast auroral waves" described by them occurred in the absence of any auroral forms other than an arc from which they apparently emanated.

Observation

Waves passing through a pulsating aurora display were seen on the morning of January 28, 1965. For more than half of this night the auroral activity was confined to an arc low on the northern horizon. At 0100 150° W.M.T. a brightening occurred in the western end of the arc. This area of enhancement, which projected slightly southward, drifted eastward along the arc at an average velocity of 330 meters/second; it disappeared after 0112.

Between 0115 and 0145 the southern boundary of the arc spread southward at about 100 m/s until the sky between 45°S and 60°N of the zenith was covered by diffuse forms. These forms were pulsating and through the entire display passed very weak southward travelling waves of light. They were seen visually to extend at least 20° or 30° east and west of the meridian and appeared to have a north-south extent of about twenty kilometers (for an assumed height of 100 km). A negative bay in the H trace occurred from 0035 to 0300 and had maximum depression at 0125 of 150γ.

The display was monitored by both an image orthicon television system having a 14° field of view and a photometer having four fields of view, each 1 1/2° diameter, on a 6° diameter circle. With the former instrument 1/60 second exposures are recorded on 16mm film at the rate of 24 per second. The S-10 photocathode surface of the image orthicon tube has a peak sensitivity at 4500Å with 10% of peak sensitivity occurring near 3200 and 6900Å. This instrument has more contrast and somewhat more sensitivity than the eye so that it can detect weaker auroral forms and provide more structural detail than the visual observer. The photometer has a 3" telescope and is equipped with a blue glass filter having 50% transmission points at 3900 and 4550Å to transmit the spectral range covered by the prominent bands of the first negative systems of N_2^+ . A set of four field stops placed in the focal plane of the objective isolates the four fields of view and directs them respectively to four RCA 1P21 photomultipliers. The anode currents are amplified by Keithley "610" electrometers and are recorded on a multichannel Ampex "SP300" tape recorder. Data on tape are transcribed to paper chart on a multichannel Honeywell "Visicorder".

As it turned out, neither instrument was ideal for the task of sorting out in situ pulsations from waves. The waves had a photometric meridional extent

of ~50-200 km, greatly exceeding the television field of view of 25 km in the zenith, and their leading and trailing edges were not sharply defined on the television films; as a result, velocity measurements could not be made from the television films. In the case of the photometer the fields of view were too close together, resulting in very small time separation between fields of view. The in situ pulsations added a complication because their photometer traces are the same as infinitely fast moving waves. In spite of these drawbacks it was possible, from the photometer records, to determine that waves passed through the display at velocities from 50 to 100 km/sec. From both the photometer and the television system it appeared that the waves only reached the southern edge of the diffuse envelope because as the latter weakened and contracted to the north through the fields of view so the detection of waves ceased.

An example of the photometer traces from fields of view at 7° and 13° south of the zenith appears in Fig. 1. Experience with similar records influenced the classification of the labelled peaks as either waves or in situ pulsations. The example is not a good one; we now have photometers with fields of view separated by 50 km which will result in greater time separation between fields of view and will also reduce the confusion caused by in situ pulsations since these are commonly less than 50 km in extent.

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- Chapman, S., and J. Bartels, "Geomagnetism", Clarendon Press, Oxford, p 452, 1940.
- Cresswell, G. R., and A. E. Belon, Observations of fast auroral waves, Planet. Space Sci., in press, 1966.

Part II Preliminary Description of a Magnetospheric Model for the Generation of Fast Auroral Waves

The observations of fast auroral waves indicate that they are very likely produced by equatorward propagating electron precipitation patterns. Suppose that there is a large population of low energy electrons with a large spread of equatorial pitch angles trapped on near-auroral-zone field lines. Further suppose that at some point we have fast mode hydromagnetic waves propagating across the field lines. Their effect will be to compress and rarefy the field in the vicinity of the chosen point. An electron which formerly mirrored there will now 'see' a mirror point that is oscillating up and down the field line. Just how far up and down will be dictated by the amplitude of the hydromagnetic wave. If the electron encounters an ascending mirror point, then, by the Fermi mechanism, its longitudinal velocity (velocity parallel to the field line) will increase by twice the mirror point velocity (Fermi, 1949). In the other case, for the descending mirror point, its velocity will decrease by the same amount. We are interested in the first case because the additional longitudinal velocity will result in a decreased pitch angle and, possibly, precipitation into the atmosphere at the other end of the field line; head-on encounters are more likely to occur.

Given suitable conditions, as a hydromagnetic wave propagates inward (towards field lines of lower L value) it will decrease the pitch angles of mirroring electrons and cause them to precipitate in a pattern that sweeps equatorward (Figure 2).

Consider the $L=5$ and 5.5 field lines of the earth's dipole field. At the 100 km level these are separated by 150 km. This distance is traversed by the fast auroral waves in about one second. It is necessary then to examine the

divergence with altitude of these field lines in conjunction with the velocity versus altitude characteristic for the hydromagnetic waves (for example, Fig. 7 Bostick et al, 1964). It appears that the first region where the transit time between the field lines is about one second is at a latitude of 20° (N or S), or about 25,000 km altitude, assuming an undistorted dipole magnetic field. The magnetic field strength in this region is about 320γ . If the wave has amplitude $50-60\gamma$ then an electron that would normally mirror at latitude 20° would encounter a mirror point oscillating with nearly simple harmonic motion of amplitude 2,500 km. Relative to the 20° latitude point the oscillation could be approximated by

$$s = 2500 \sin \omega t$$

$$\text{so, } \dot{s} = 2500 \omega \cos \omega t$$

We select $\omega = 2\pi$ radians/sec in accordance with the observations and then see that the maximum mirror point velocity is 16,000 km/sec. Therefore the maximum velocity increment imparted to an electron would be 32,000 km/sec.

An electron mirroring at 20° latitude on the $L=5.5$ field line will have an equatorial pitch angle of 50° ; the ratio of the transverse velocity to the longitudinal velocity will be $\tan 50^\circ$, or 1.2. Denote the longitudinal velocity by v_s , then v_n , the transverse velocity, is $1.2 v_s$. After encountering the ascending mirror point, at the midpoint of its motion, and returning to the equatorial plane the electron will have velocities:

$$v'_s = v_s + 3.2 \times 10^9 \text{ cm/sec}$$

$$v'_n = v_n = 1.2 v_s \text{ cm/sec}$$

Let us impose the condition that the electron precipitates into the atmosphere as a result of the one head-on encounter with the ascending mirror point. Then its equatorial pitch angle must have changed from 50° to 3°

(or less), i.e.

$$\tan 3^\circ \approx .052 \approx \frac{v_n}{v_s} = \frac{1.2v_s}{v_s + 3.2 \times 10^8}$$

Therefore $v \approx 1.5 \times 10^8$ cm/sec

$v \approx 2.3 \times 10^8$ cm/sec

where $\vec{v} = \vec{v}_s + \vec{v}_n$ is the total velocity of the electron initially.

Thus initially the electron had energy 15 ev. (or less). Its final velocity will be 3.4×10^9 cm/sec, an energy of about 3 kev.

This mechanism would produce fast auroral waves of almost steady intensity if a homogeneous population of such electrons was available. If it were inhomogeneous then the intensity could vary as the waves went across the sky. Waves with different velocities would be produced by the mechanism acting at different places on the field line.

Energy Considerations

Chamberlain (1961), page 283, calculated that an aurora of brightness 100 kR in $\lambda 3914$ had an energy of ionization deposited into it of 2.5×10^{14} ev/cm²sec. From the fast auroral wave observations the $\lambda 3914$ intensity is about 1 kR and so the energy deposited is 2.5×10^{12} ev/cm²sec (1.6 ergs/cm²sec). Treat a strip 1 cm wide and 150 km long; the energy deposited into this to produce 1 kR of $\lambda 3914$ for one second is 2.4×10^7 ergs. Reduce this by a factor of 1/2 to get 1.2×10^7 ergs since for a fast auroral wave the whole strip is not emitting for a full second.

This strip transforms to one 5 cm wide and 2,000 km long in the magnetosphere at conjugate latitude 20°. Since we have taken the influence of the hydromagnetic wave to range longitudinally about 5,000 km we finish up with a

slab. Hydromagnetic energy is introduced into this slab through the 5 cm by 5,000 km edge. The wave energy density = $\frac{b^2}{8\pi}$ ergs/cm³ where \vec{b} is the wave magnetic vector. The Poynting vector = $(\frac{b^2}{8\pi} \times \text{wave velocity})$ ergs/cm²sec

Total energy introduced into the slab in 1 second

$$= \frac{b^2}{8\pi} \times 2000 \times 10^5 \times 5 \times 5000 \times 10^5$$

$$= \frac{(50 \times 10^{-5})^2}{8\pi} = 5 \times 10^9 \text{ ergs}$$

Thus the energy introduced into the slab exceeds, by a factor of about 400, the energy lost to electrons to produce the strip of a fast auroral wave that travels 150 km. In other words, the hydromagnetic wave will have adequate energy to produce the fast auroral wave.

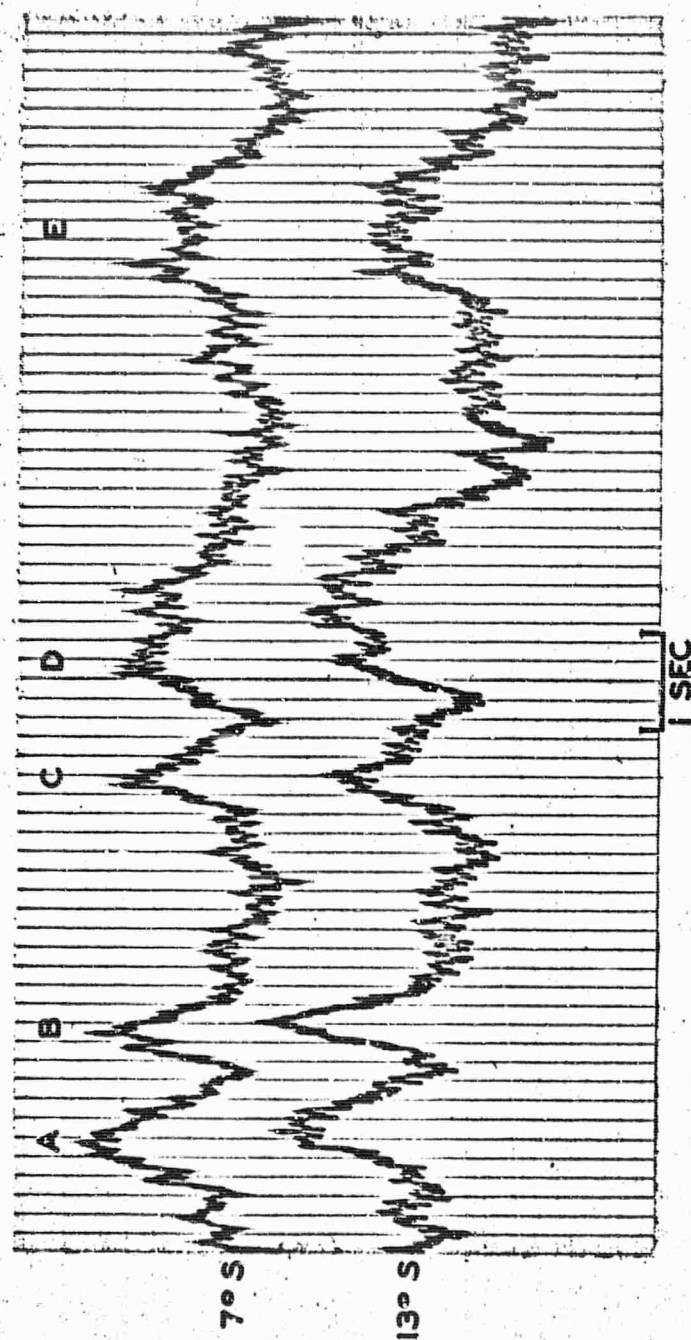
Satellite Observations

Sonett et al (1962) demonstrated the presence of various hydromagnetic wave modes at geocentric distances 3.7 to 7 earth radii on the sunlit hemisphere during magnetically quiet surface conditions. The longitudinal (fast) mode had a strong component of about 1 cps and amplitude 10-20Y.

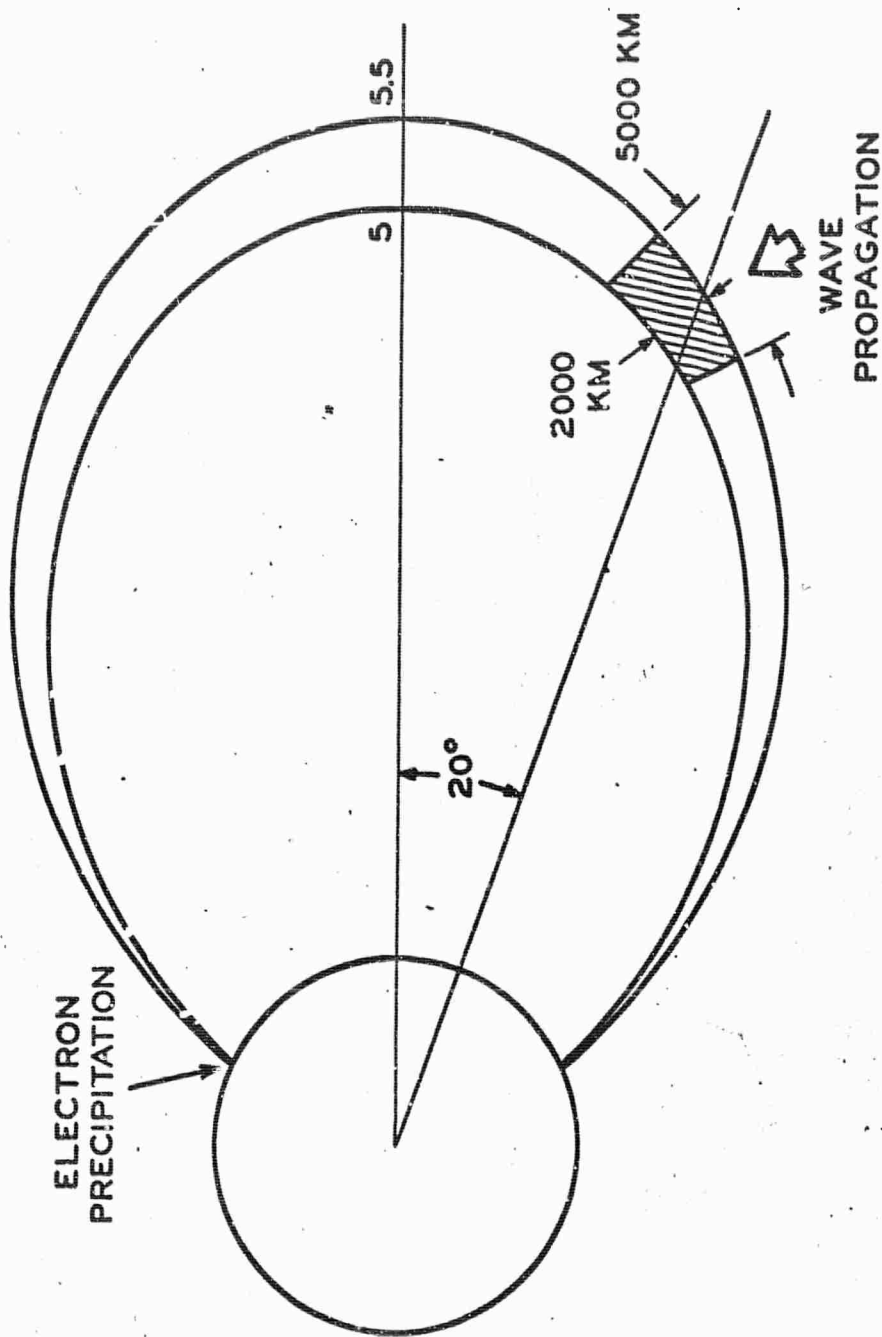
This observation has been cited here merely to show that the hydromagnetic wave fast mode exists in the magnetosphere and has an amplitude of the same order of magnitude (even if on the sunlit side) that we require.

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TASK B Figure 1. Photometer traces from fields of view 7° and 13° south of the zenith ($13^\circ S$ is the magnetic zenith at College). Peaks A through E were interpreted to be due to: a wave, a wave, an in situ pulsation, a wave, and an in situ pulsation respectively. Waves A, B, and D had velocities: 70, 100, and 70 km/sec, and widths: 90, 70, and 170 km.



TASK B Figure 2. Schematic diagram for the fast auroral waves model. The two field lines shown are separated by 150 km at an altitude of 100 km in the vicinity of College. Fast mode hydromagnetic waves are thought to propagate inwards (as shown) and cause longitudinal oscillation of electron mirror points in the shaded region. Fermi accelerated electrons then precipitate in equatorward propagating precipitation patterns in the College vicinity.